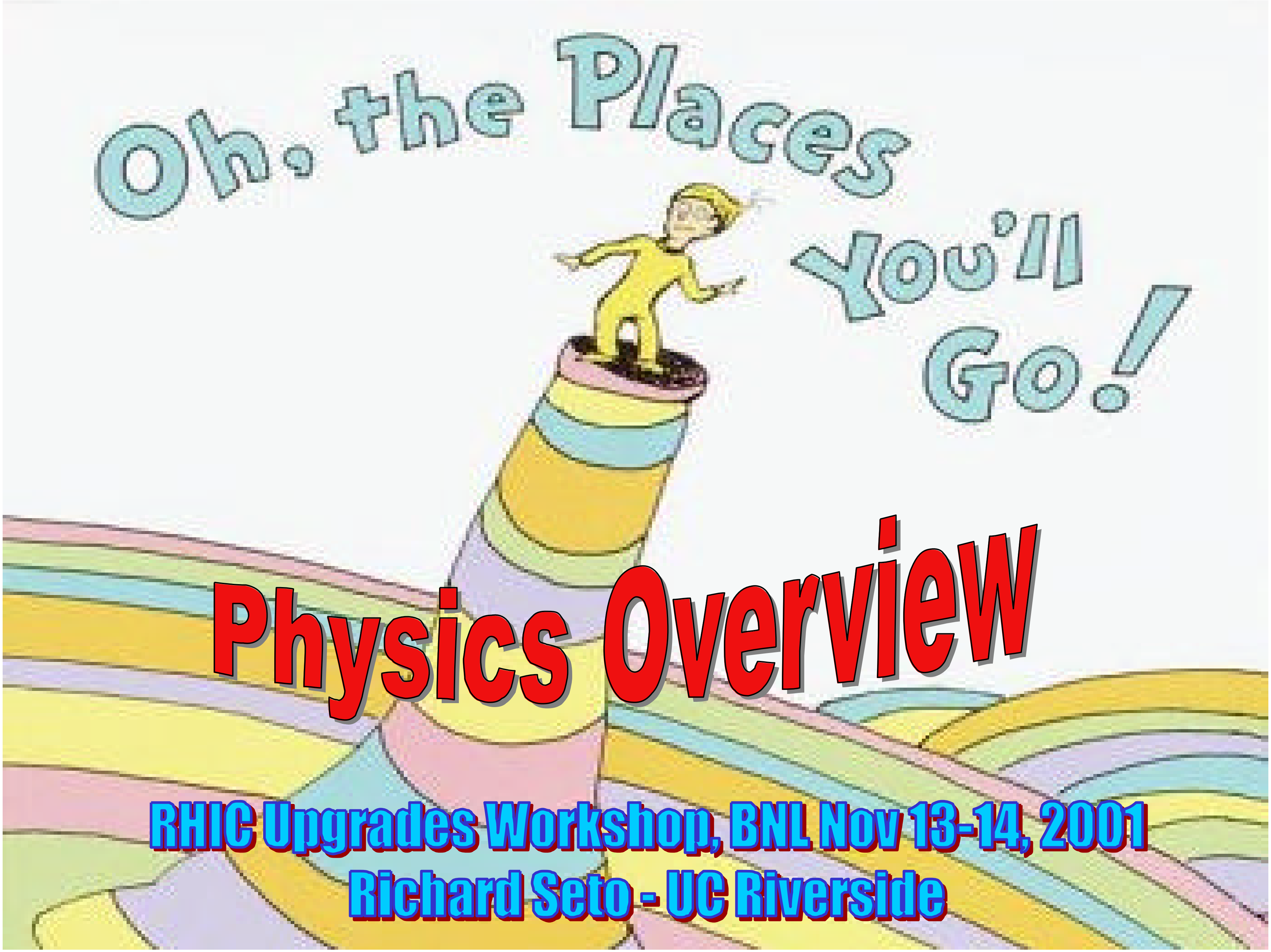


Physics Overview

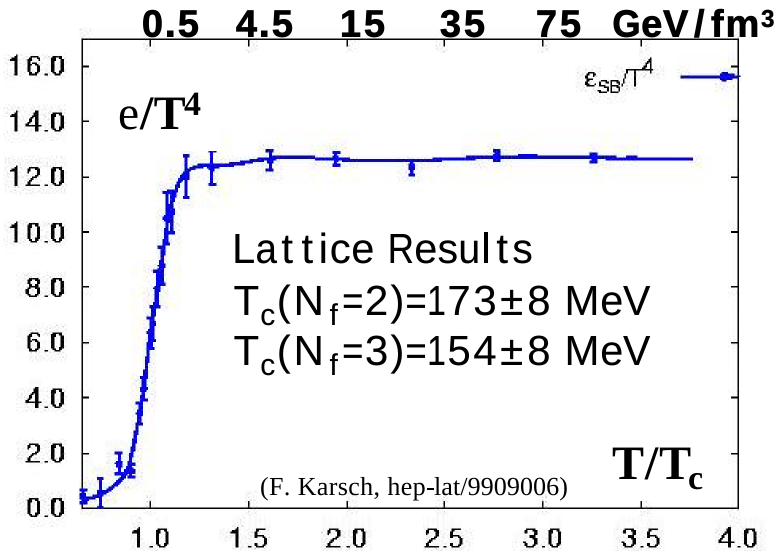
RHIC Upgrades Workshop, BNL Nov 13-14, 2001

Richard Seto - UC Riverside

Outline

- Where are we?
  - What have we measured?
  - What have we learned?
- What next? (LRP)
  - What would we like to know?
    - The growth of theory and experiment
  - What must we measure?
    - An era of precision measurements
- How do we do it?
  - Detectors requirements (AA,pA,pp)
  - Machine requirements
- Some closing remarks

What have we measured? Global Features: dE_T/dy ~ Initial Energy Density



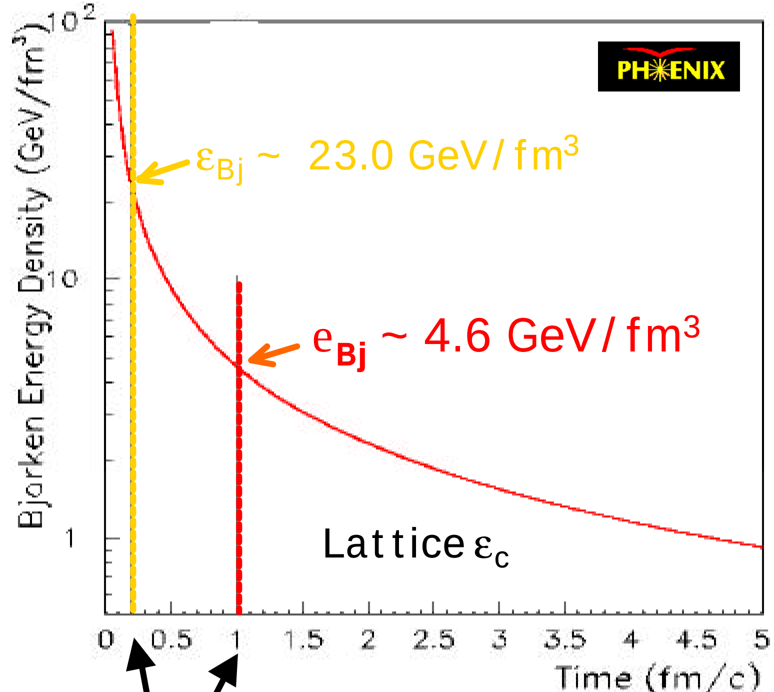
T = 150-200 MeV

$\varepsilon \sim$ 0.6-1.8 GeV/fm^3

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau_0}\left(2\frac{dE_T}{dy}\right)$$

PHENIX: Central Au Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\ GeV$$

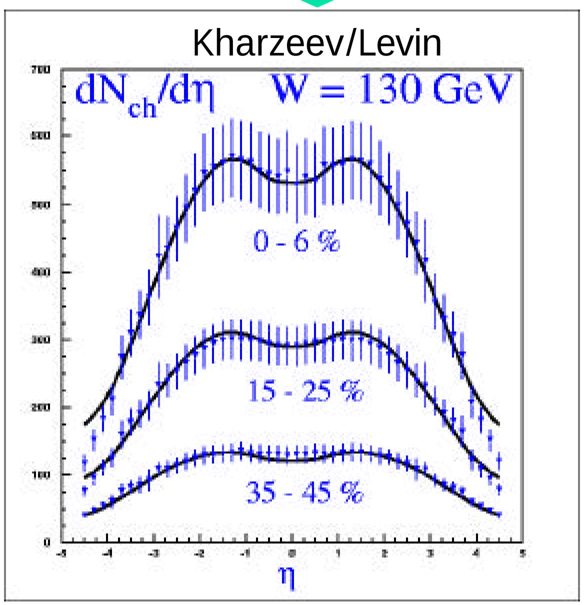


Thermalization time ?

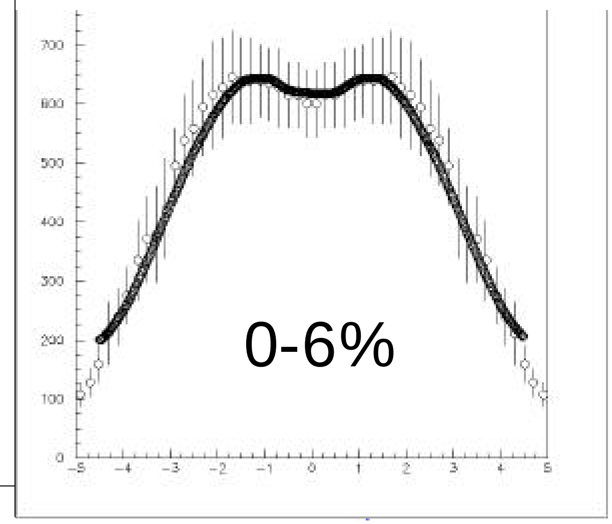
High Initial energy density- Favorable for the formation of a QGP

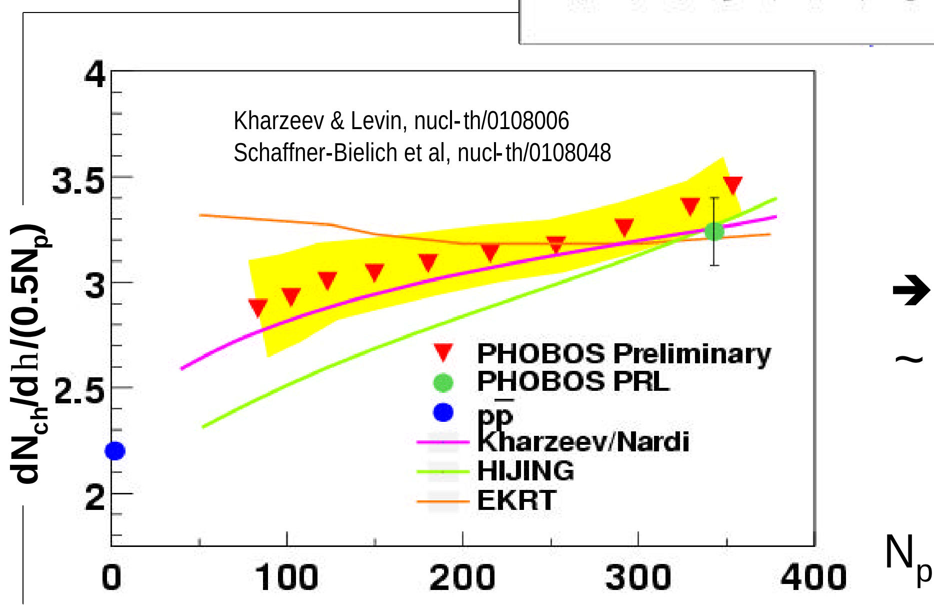
What have we measured? Global Features: Saturation?

Saturation models can predict the scaling with centrality and energy dependence!



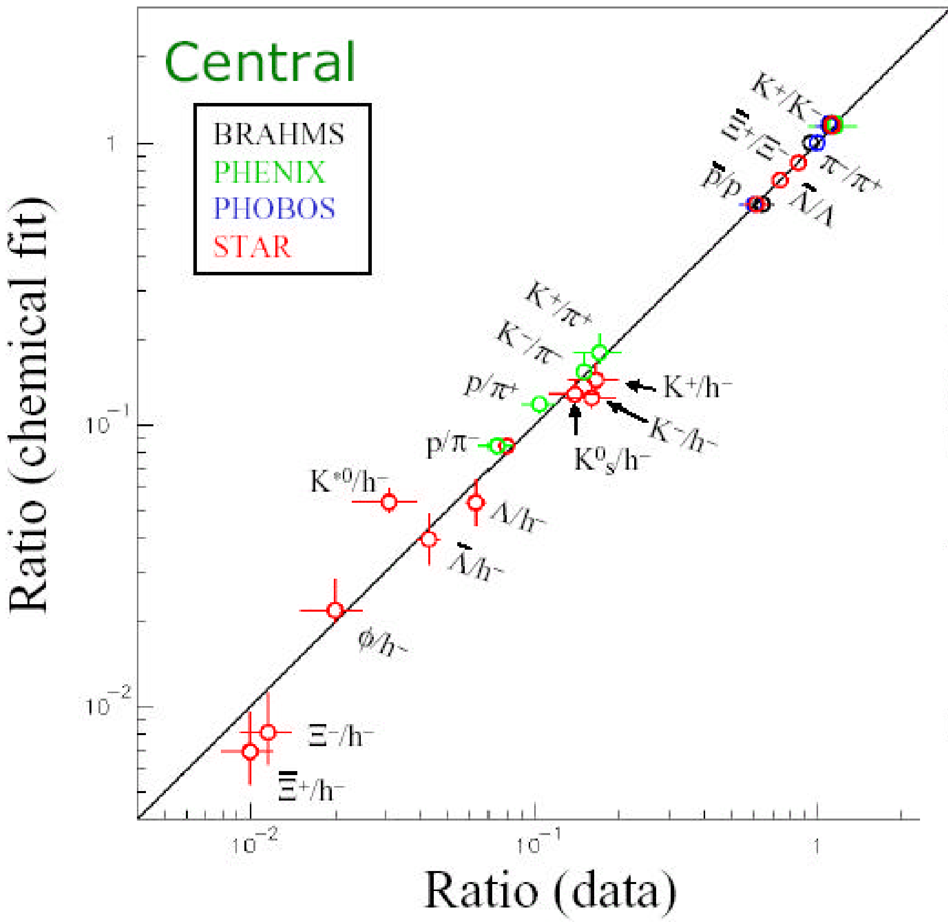
Kharzeev/Levin Prediction vs Phobos 200 GeV data!





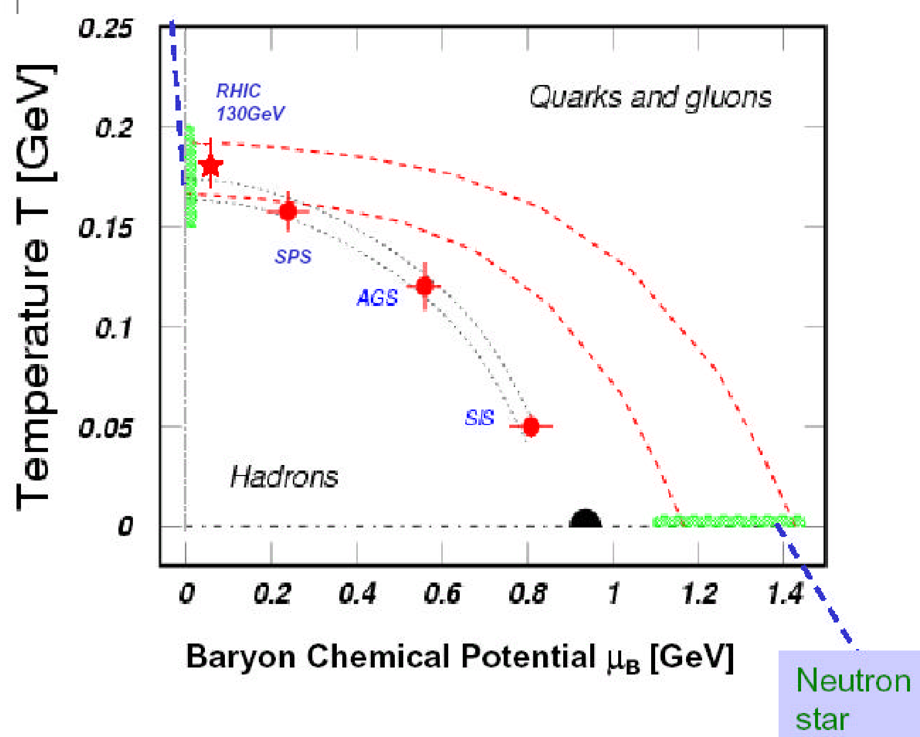
→energy density ~18GeV/fm^3

What have we measured? Global Features:
Chemical Equilibration



From yields

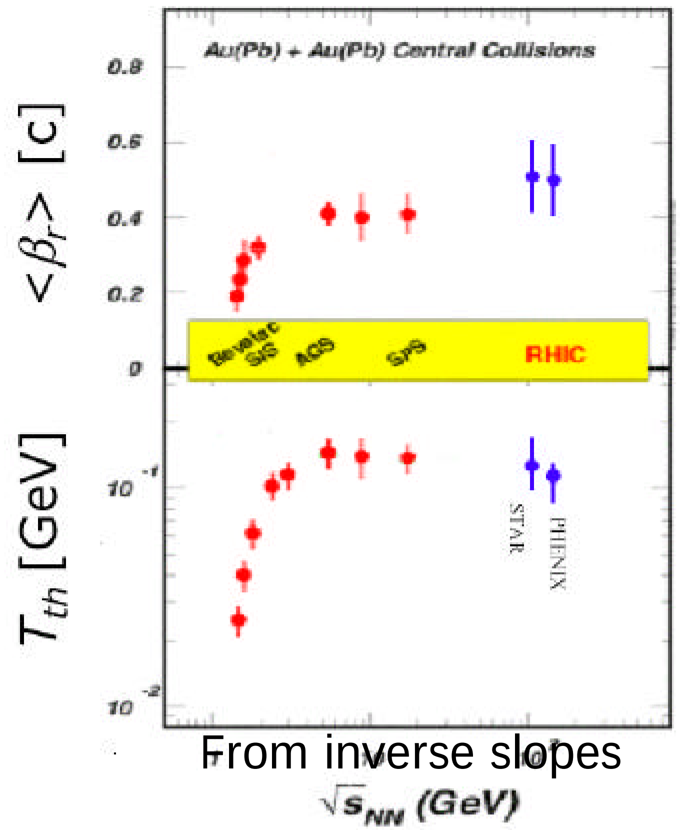
Model assuming Chemical Equilibration describes yields Pretty well ➔ $g_s \sim 1$



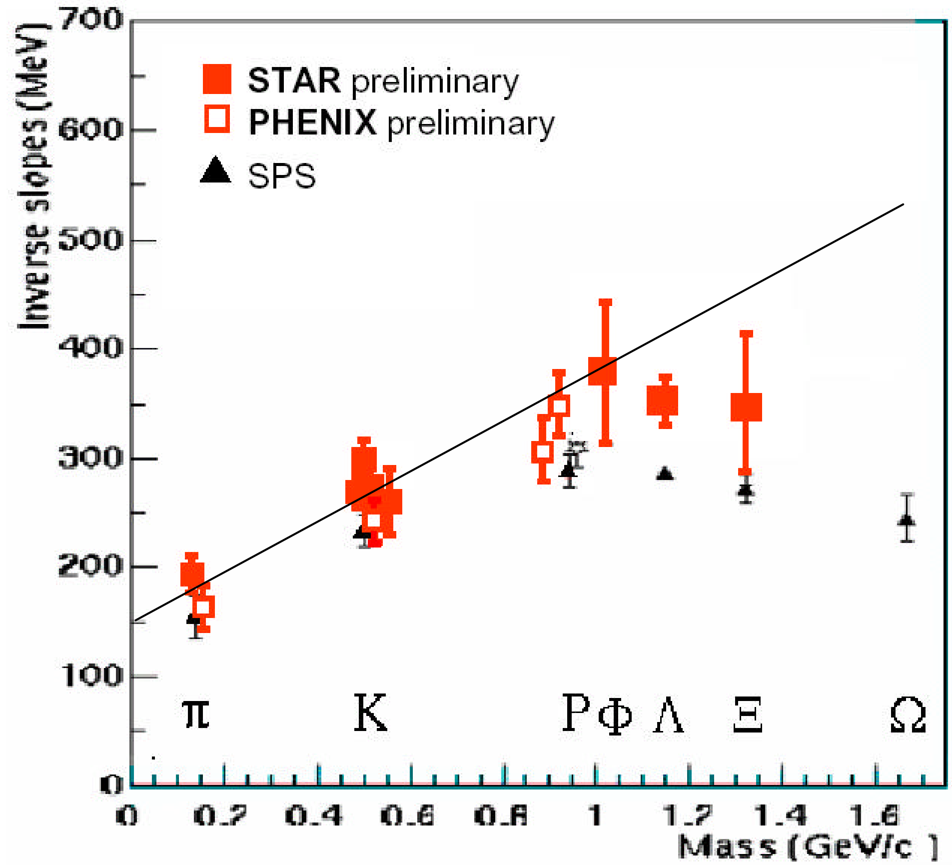
parton-hadron phase boundary

<E>/<N>~1GeV, J.Cleymans and K.Redlich, PRC60 (1999) 054908

What have we measured? Global Features:
Thermal equilibration



From inverse slopes



$T_{thermal\ freezout}$ ~ 130 GEV ~AGS/SPS

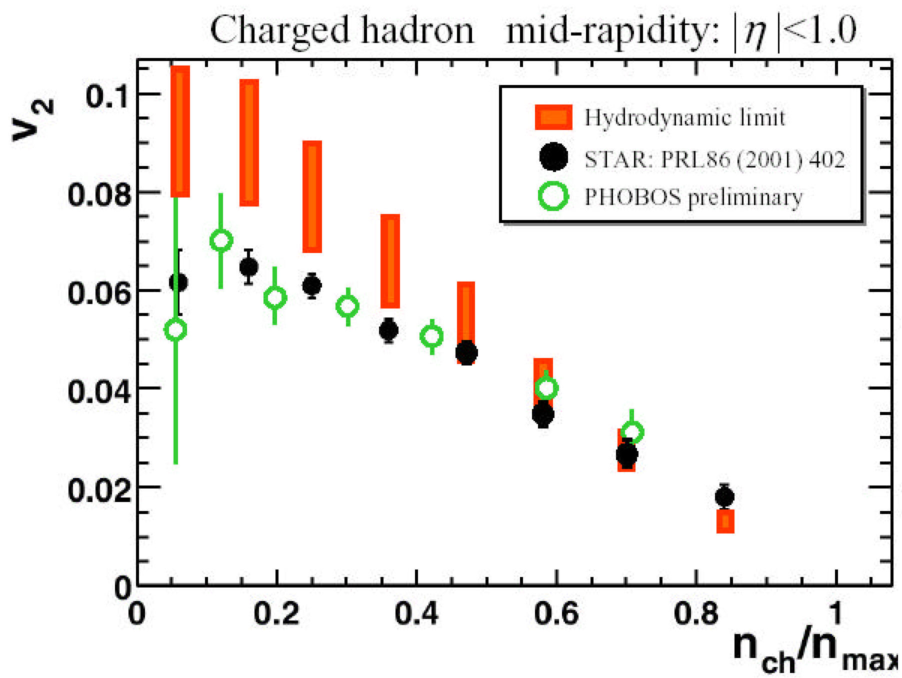
b_{radial} increases to ~ 0.5

As at SPS Strange particles Freeze out earlier

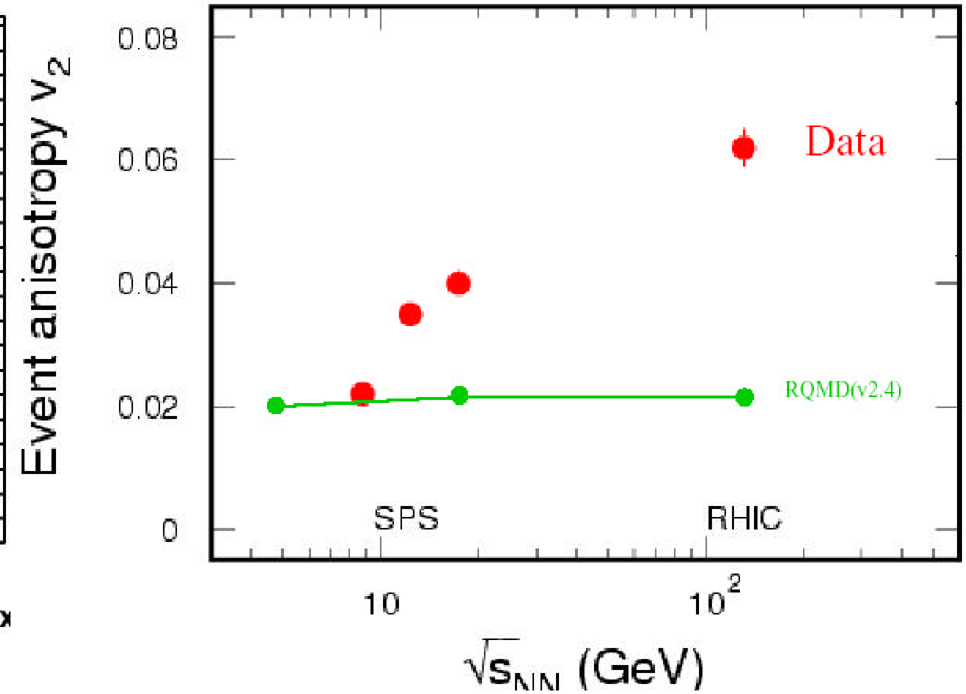
Explosive radial expansion ➔high pressure

What have we measured? Global Features:

Elliptic Flow



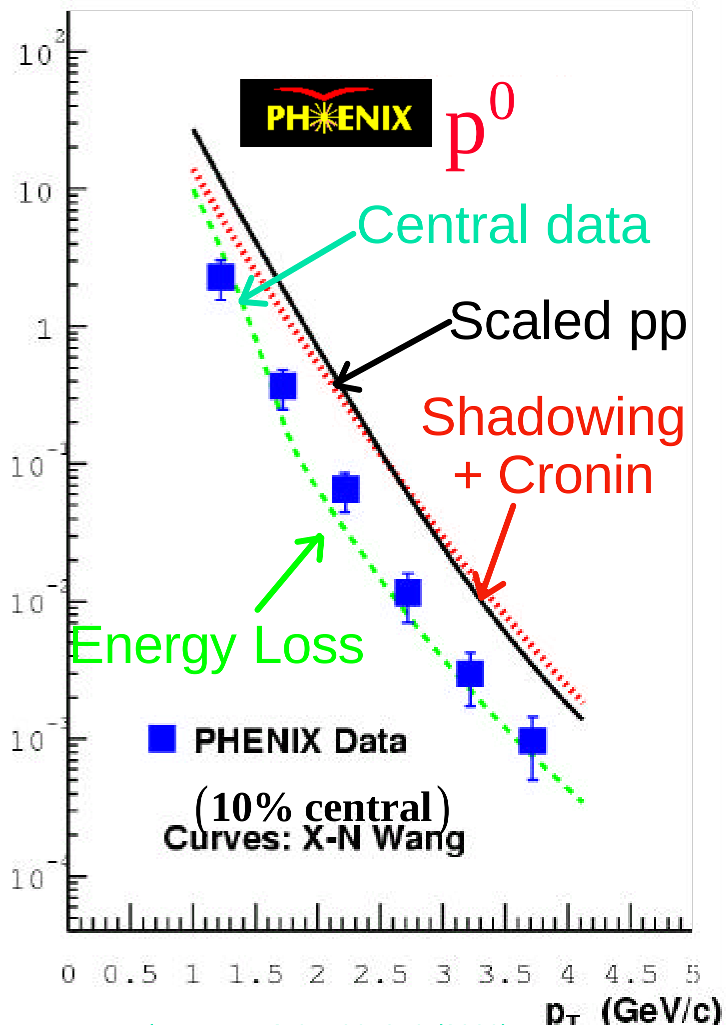
(PHOBOS : Normalized Paddle Signal)



Very strong elliptic flow
Early thermalization

Hydrodynamical model (Kolb et al)
➔Rapid thermalization t_0 ~ 0.6 fm/c
➔ε~20 GeV/fm³

What have we measured? Probes:
Energy Loss from π^0



X.N. Wang, Phys. Rev. C 61, 064910 (2000)
(nucl-th/9812021)

High Pt spectra

Calculation of X.N. Wang includes a particular shadowing parameterization for the structure functions and kT broadening (Cronin).

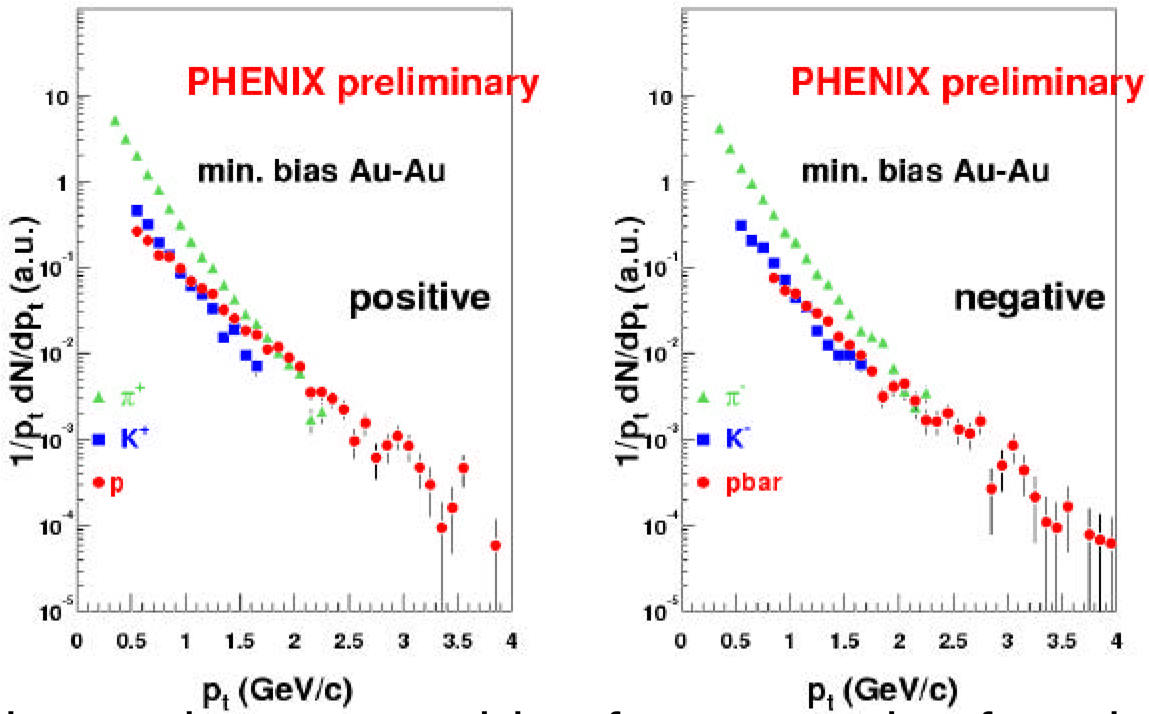
Agreement with data implies:

dE/dx = 0.25 GeV/fm

Jet quenching???

Jet Fragmentation?

proton/antiproton contribution above p_T > 2 GeV dominates charged spectra !
Hydrodynamics (M_T Spectra) vs Jet fragmentation (p_T Spectra)



This is not the expected jet fragmentation function D(z).

PID at high PT necessary upgrade

What have we measured? Probes:

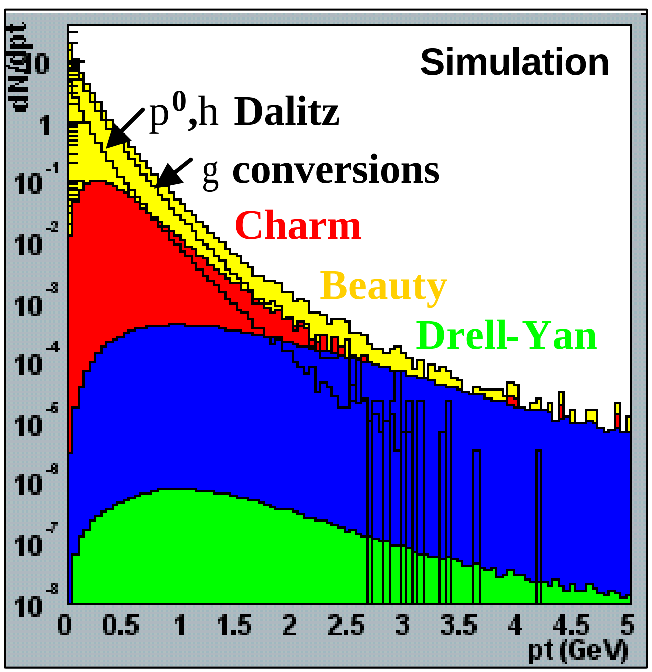
Single Electron Spectra

One must account for contributions:

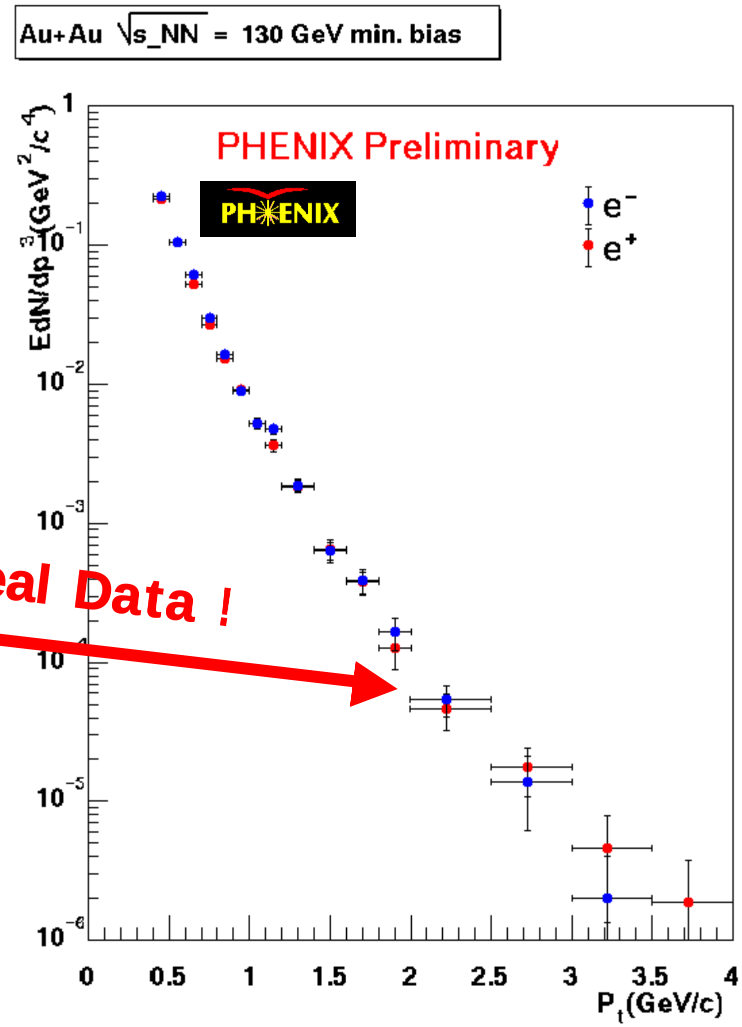
- π^0, η Dalitz
- γ conversions

Remaining signal is then from

- charm and bottom
- thermal production
- new physics



Now Real Data !



Lepton probes beginning!

What have we learned?

- We have made rapid progress on the global features of the system
  - Initial energy density is high – favorable for the formation of a QGP
  - Saturation approach seems to work!
    - Ös, b dependence OK
    - Initial or final state effect?
      - Need pA data
  - Matter appears thermalized
    - T_f does not grow with Ös
    - b_r grows with Ös
    - ® Same phase boundary, but pressure increases with Ös
  - Strong early pressure build up – rapid thermalization
    - Large p_T are at early times- but loose energy
    - ® system is very dense – it is not a free streaming parton system (a Liquid?)
- Probes of the system are just beginning
  - Indications of Jet quenching
    - Need to see transition from hydro (thermalized system) to high p_T partons
      - I.e. plot switches from m_T to p_T
  - Lepton measurements beginning

What Next?

- 2001/2002
  - L = ?x10^{26} 12 weeks @200
    - All detectors – Hadronic signatures, high p_T
    - STAR – event by event studies, W, resonances
    - PHENIX
      - Leptons begin (barely)
        - J/ψ to ee,mm
        - f to ee,KK
  - Pp
    - L=5x10^30 pp 5 weeks, 7/pb, pol ~0.5
    - First measurement of gluon polarization (A_{LL}) and A_N (?)
    - Crude pp comparison run
- 2003 – 2005
  - RHIC ***x4 increase in Luminosity ?***
    - Nice steady running
  - Heavy Ions
    - STAR adds leptonic (electron) signatures
    - PHENIX does leptons,photons
    - Brahms Coverage to γ~4
    - Steady Luminosity AuAu runs
    - Light Ions runs
    - Energy changes
    - Baseline pp, dA runs!!
  - Pp
    - All spin rotators in, Pol~0.7
    - 200 and 500 GeV runs
    - Star adds photon+Jet signature
    - Phenix adds Heavy Quark trigger
    - Physics
      - Gluon polarization
      - Parity violating W production
      - Anti-quark polarizations, W,DY
      - Transversity studies begin

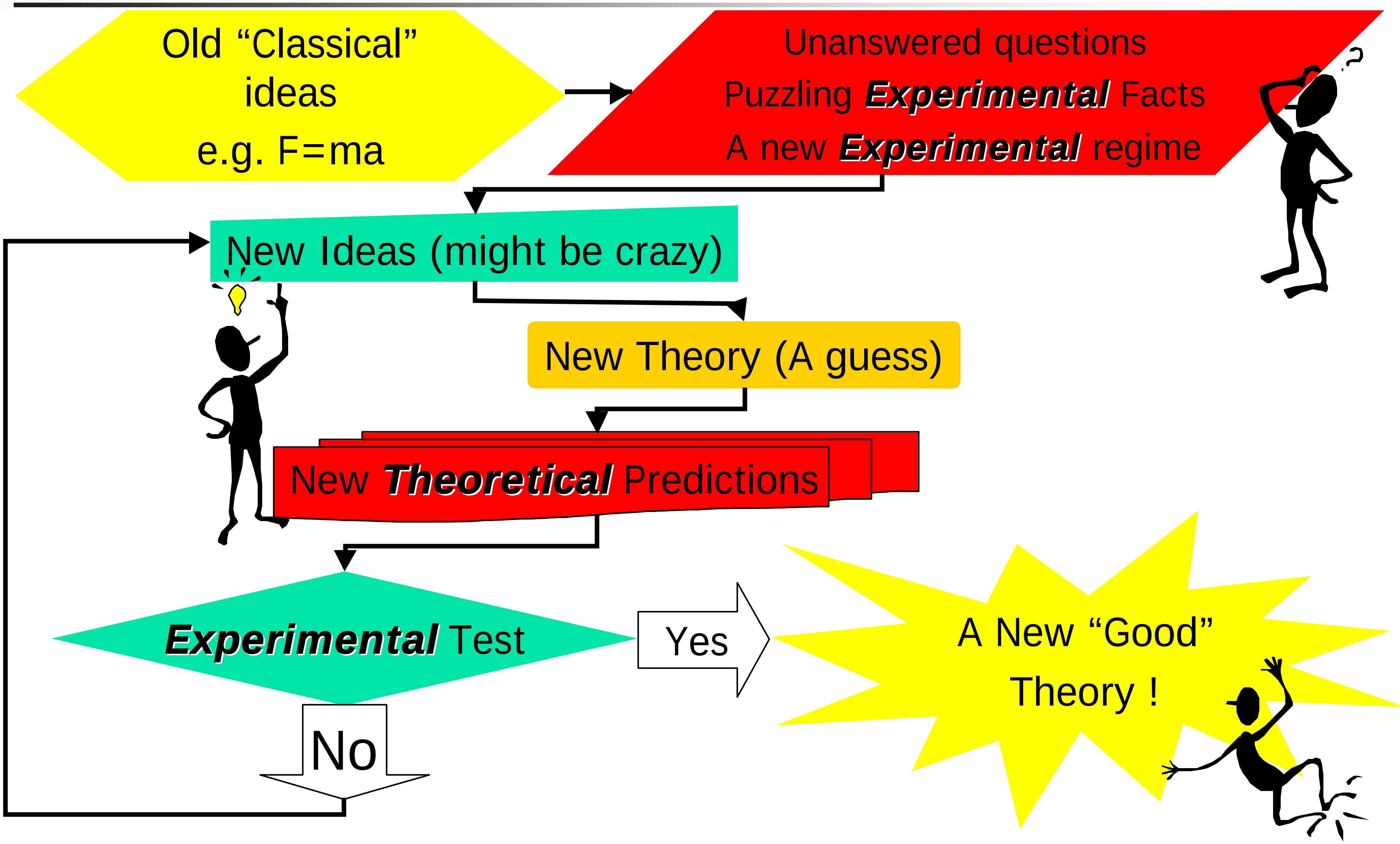
Pause

- We (RHI experimentalists) think classically – our QGP (or hadronic gas) is little balls buzzing around in an expanding balloon
  - In the world of electrons we wouldn't have
    - Conductors/Insulators
    - Semi-conductors.
  - Like us to start thinking as quantum mechanics
    - Tough to understand – but take some limits
      - High temp limit – Quantum statistics
      - High occupation number limit, Saturation Ideas
    - Looking at around the phase transition
      - Interesting Quantum effects come in
        - Masses?
        - Confinement?

quotes from Jaffe at Spin 2000

- Spin has recently proved itself a very powerful tool to probe the internal structure of hadrons in QCD. We have measured the quark spin contribution to the spin of the nucleon, but we do not understand it. In fact, we know more about the spin of the graviton, which has never been observed, than we do about the spin of the nucleon, which composes most of the luminous mass in the Universe.
- I expect that spin will continue to surprise us as it has in the past. The reason is that spin is fundamentally quantum mechanical in its origins so that it beggars our classical intuition.

How do we understand?



RHIC has introduced a region where this cycle can occur

Demands and opportunities

- ➔ Theory + Experiment = Understanding
  - ***Theoretical Calculations*** in regions probed by ***experiment***
  - ***Experiments*** in regions calculable by ***theory***
- ➔ New era of Precision
  - Precision ***Calculations***
  - Precision ***Measurements*** (this workshop)
    - Precision Detectors
    - High Luminosity
  - AA, pA (dA), pp, eA

Example 1 – Understanding our system of bulk matter

- *Theoretical* understanding
  a) In thermal equilibrium
    - is pretty good
  b) In single nucleus
    - *Theor*y using Random classical fields – Saturation
    - Check this out with *Experiments* eA, pA
- RHIC *Experiments* will be needed to understand transition between a) and b)

Example 2 – Understanding the right Degrees of Freedom

- Superconductor – Condensed matter
  - DOF
    - Electrons?
    - Phonons?
    - Really – Cooper pairs
  - Calculation-Theorists “guessed” the right DOF
- QCD matter
  - DOF
    - Quarks
    - Hadrons?
    - Something in between?
- properties of hadrons at high T or r_B
  - Assumptions of
    - Brown-Rho scaling: hadron masses scale as the quark condensate - a quark degrees of freedom point of view
    - Rapp-Wambach: Rescattering and cross sections – a hadronic degrees of freedom point of view
  - Duality?: hadronic • quark degrees of freedom
  - To actually prove this is not possible at the moment.
  - Theorists will depend on experiment to help define the right “degrees of freedom” to use
- Calculation
  - Right now we use brute force – the lattice
  - If we find the right DOF -Understanding of
    - transition – chiral symmetry
    - Transition – confinement
      - Other new phenomena

“Questions”, from LRP white paper

- What are the properties of the QCD vacuum and its connection to the masses of the hadrons? What is the origin of chiral symmetry breaking?
- Can we locate signatures of the deconfinement phase transition as the hot matter cools? What is the origin of confinement?
- What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?
- In Relativistic Heavy Ion Collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved

LRP questions: What should we measure?

- The QCD vacuum
  - Mass?
  - Chiral Symmetry?
  - Transition T
- Confinement?
  - Signatures?
  - Transition T?
- Properties of matter at high energy density? Quarks and gluons correct?
- Understanding the system Created in Relativistic Heavy Ion collisions

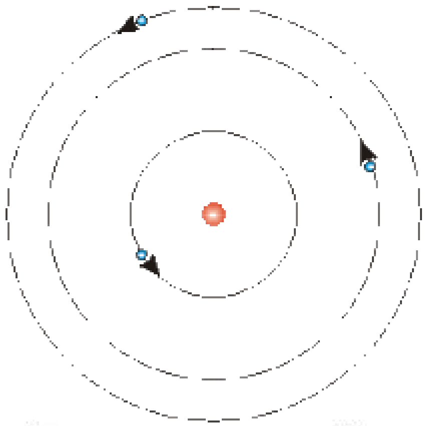
- What would we like to measure?
  - Low mass VM in lepton channel vs energy density
  - Critical phenomena
  - Quark and gluon energy loss
    - Reaction plane
  - J/y, U
  - Open charm
  - Thermal
    - Photons
    - Dileptons
  - low-x phenomena
  - Strange/ anti-baryons, p_T spectra
  - HBT
  - Flow
  - Temp/Size/Time profile of the system

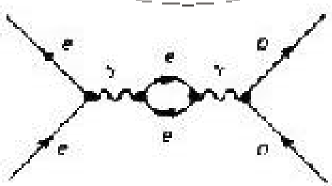
What do we need to do to make the measurement?

- What would we like to measure?
  - Low mass VM in lepton channel vs energy density
  - Critical phenomena
  - Quark and gluon energy loss
    - Reaction plane
  - J/y, U
  - Open charm
  - Thermal
    - Photons
    - Dileptons
  - low-x phenomena
  - Strange/ anti-baryons, p_T spectra
  - HBT
  - Flow
  - Temp/Size/Time profile of the system

- What additional tools do we need?
  - Varying energy,species, pp,pA,dA
  - Low mass dileptons – need dalitz rejection
  - Low pt photons
  - Very Low p_T particles
  - Redundancy in lepton signatures
  - High rate
    - more Luminosity
    - High bandwidth
    - Good triggering
  - Very accurate Vertexing
  - Large coverage
  - Event by event capability
  - High p_T PID
  - Forward detectors

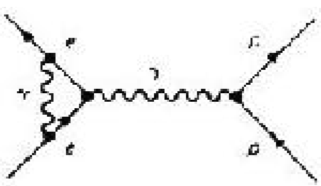
Precision measurements (examples ->exp requirements)
The “Lamb Shift” – a probe of the vacuum



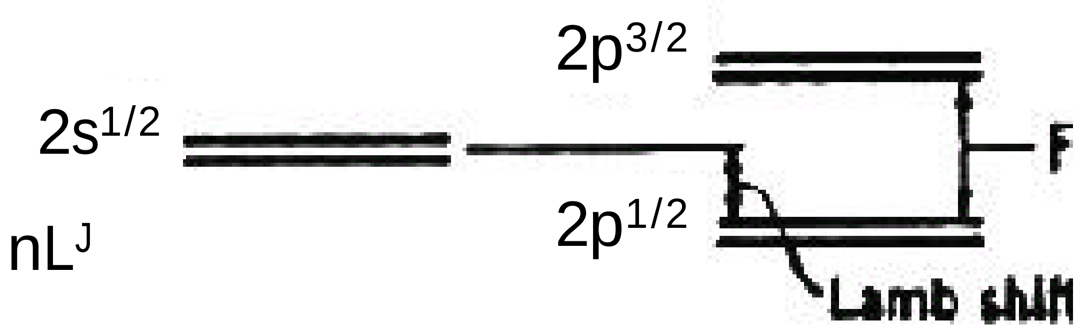


Vacuum polarization

Mass renormalization

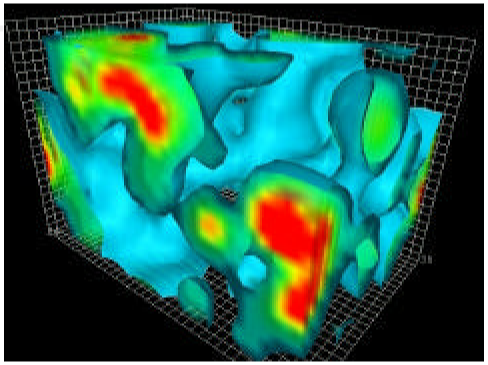


Anomalous magnetic moment

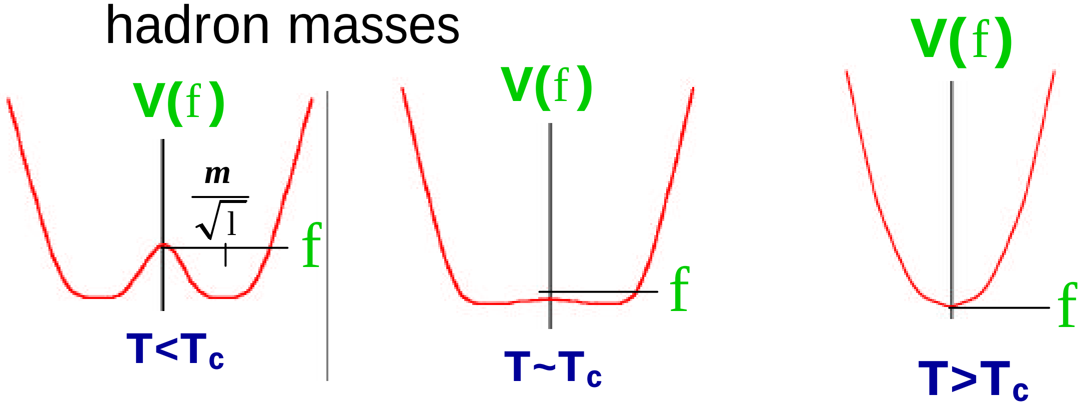


- According to standard QM, atomic states with the same total angular momentum should have the same energy level.
- In 1947 Lamb and Retherford showed that states with the same total angular momentum but different orbital angular momentum had different energy levels.
- This is due “mass shift” of the electron due to vacuum fluctuations
- One of the most accurately calculated and measured quantities in physics
- Can we do the same?

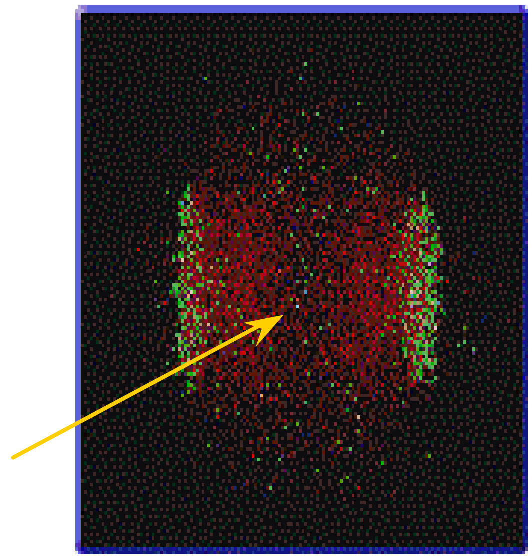
The QCD vacuum – the source of mass



- Space filled with a condensate $\phi = \bar{\psi}\psi$
  - Similar to the higgs field for E-W theory
  - $\bar{\psi}\psi$ - goo of quarks and gluons
  - Couples to quarks and gluons
  - Spontaneous symmetry breaking (I.e. chiral) of the quark condensate at low Temperature generates hadron masses

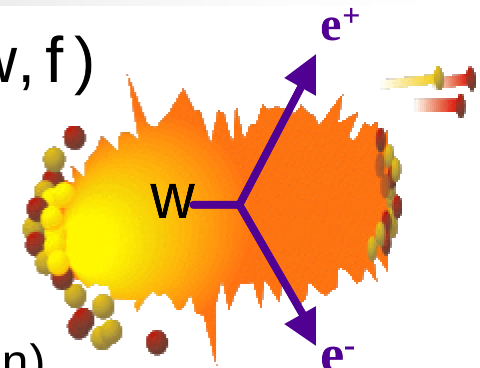


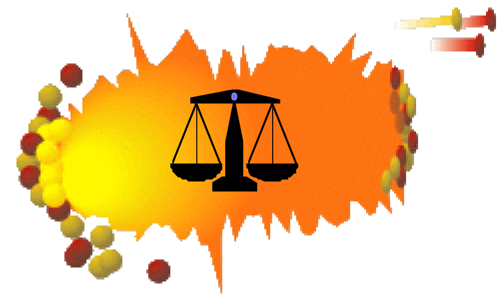
  - As $T \rightarrow T_C$, mass $\rightarrow 0$
  - How do we heat up the vacuum?
  - RHI collision leaves a region of excited $\bar{q}q$, g – ie hot vacuum



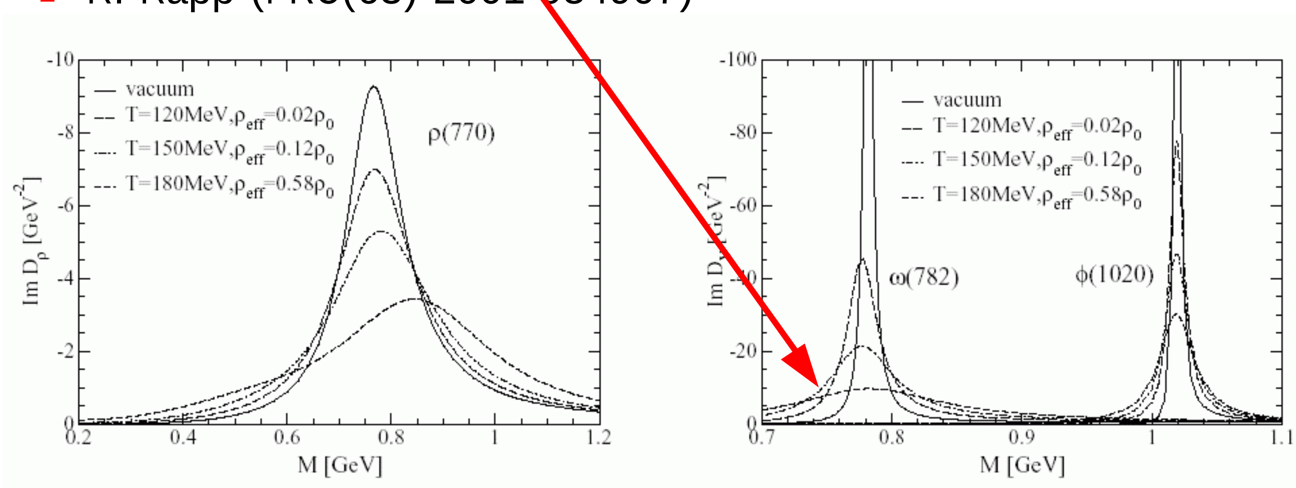
Precision Measurements Vector Meson mass shifts in the dilepton channel - the “Lamb Shift” of QCD

- “Light” Vector mesons are ideal probes (r,w,f)
  - Short lifetime ~ few fm/c
    - Decay inside the medium
  - Electrons (and muons) are ideal messengers
    - Don’t interact strongly (e.g. neutrinos from the sun)
  - ➔ Like putting a scale to measure mass inside the fireball



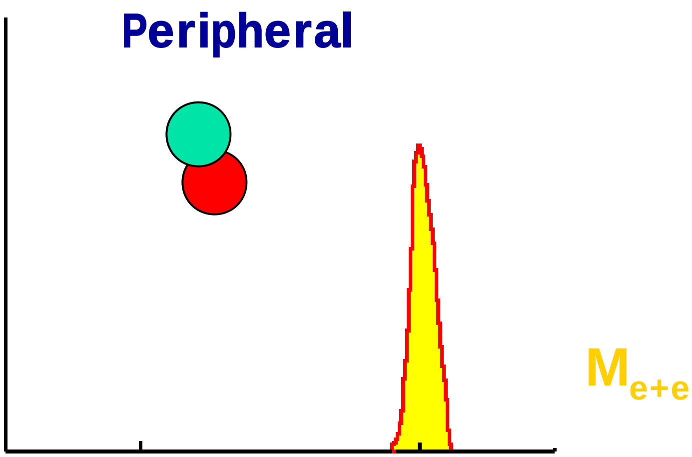


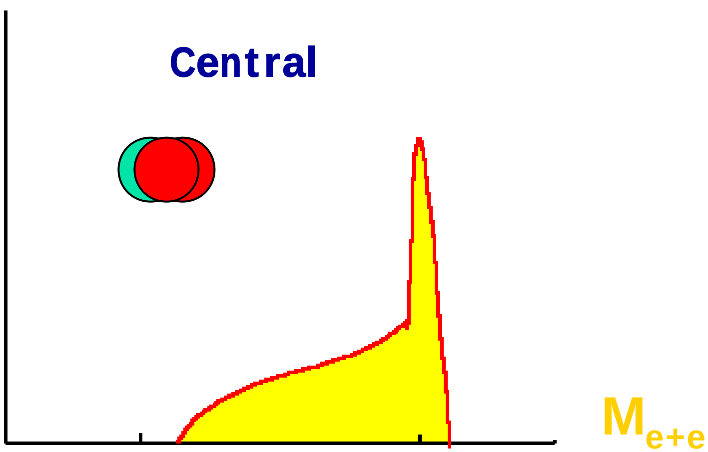
- rwf show a broadening at high T -
  - R. Rapp (PRC(63) 2001 954907)



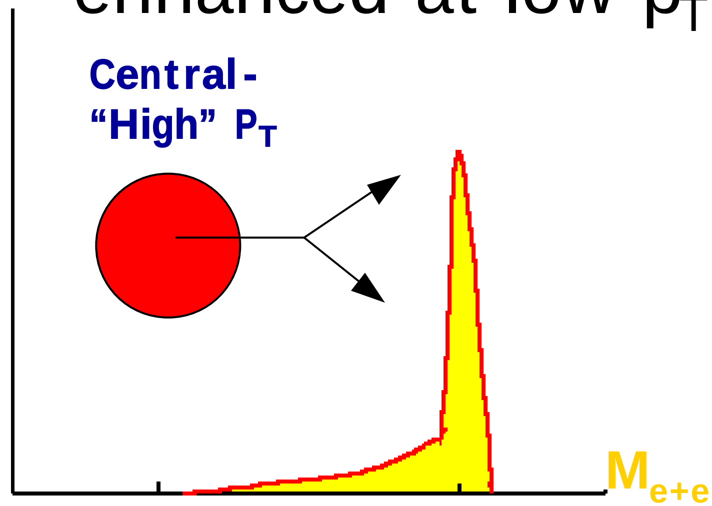
Experimental "Knobs"

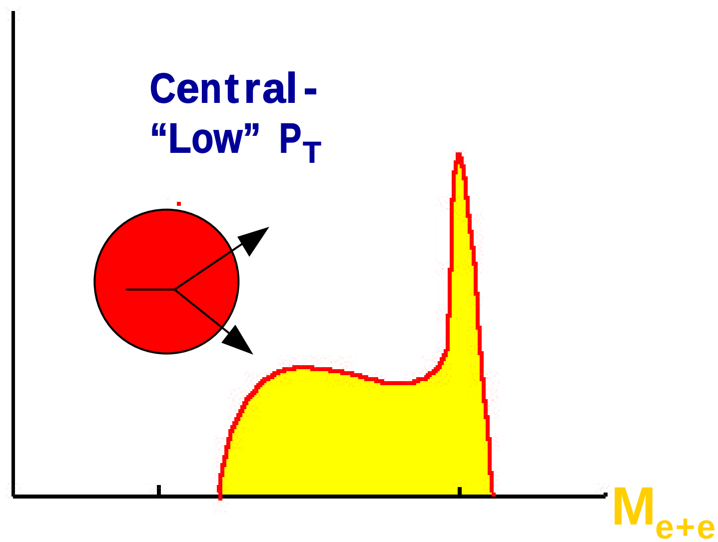
- Signal should increase with centrality





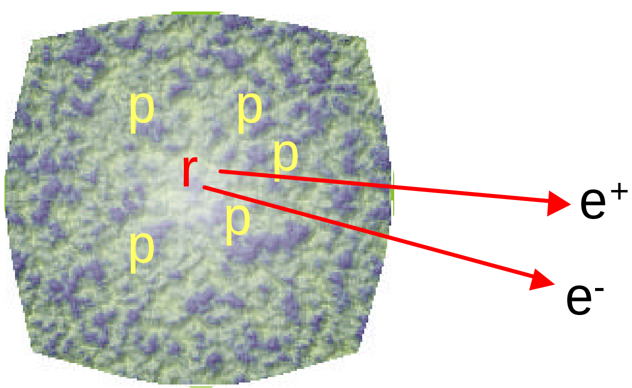
- Signal should be enhanced at low p_T





What are the problems?

- Problem – background from dalitz decays and conversions
  - *Dalitz rejection via electron ID in a field free region.*
  - Critically important to see vacuum values to prove mass resolution is good – I.e. you want to see a “peak”
    Good momentum resolution
  - An added benefit – sensitivity to mixed phase lifetime
    - Strong enhancement of the r (mixed and hadron gas phase)
      - p have a very short mean free path in the hadronic gas
      - r has a very short lifetime (<1 fm)

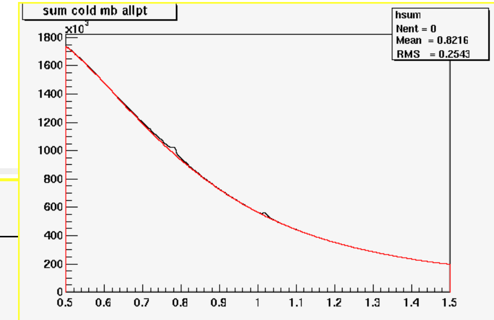


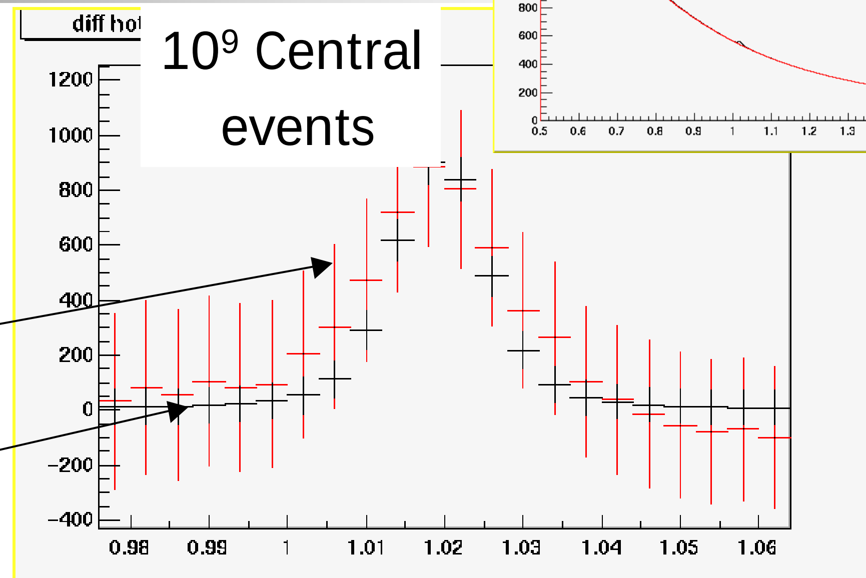
pp®r®pp®r®pp®r®pp®r®pp®r®

↳ e^+e^- ↳ e^+e^- ↳ e^+e^- ↳ e^+e^- ↳ e^+e^-

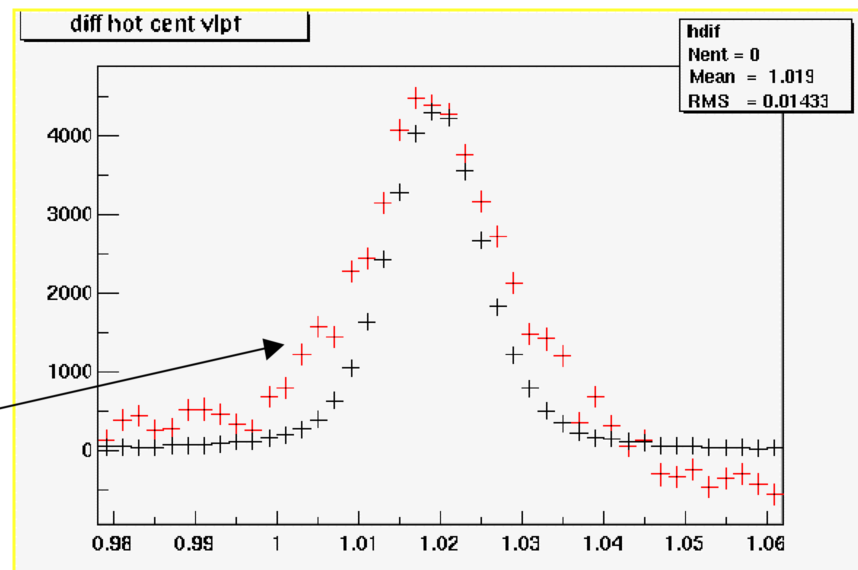
A precision measurement the f line shape

- Plots are for
  - Central events pt<0.2 GeV (red) compared to
  - high pt peripheral renormalized (black)
- With statistics of 10^9 Central and no dalitz rejection it is not possible to see the width broadening
- After factor of 100 suppression of background from dalitz rejection (kill 90% of combinatorics)

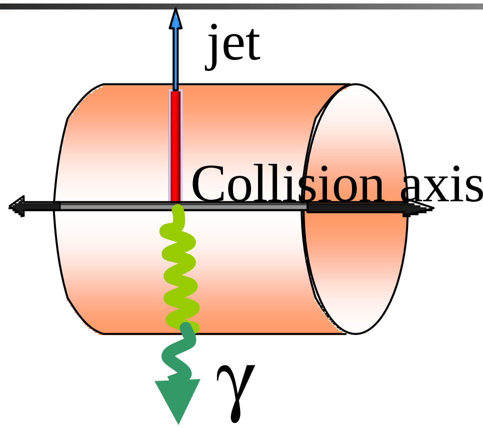




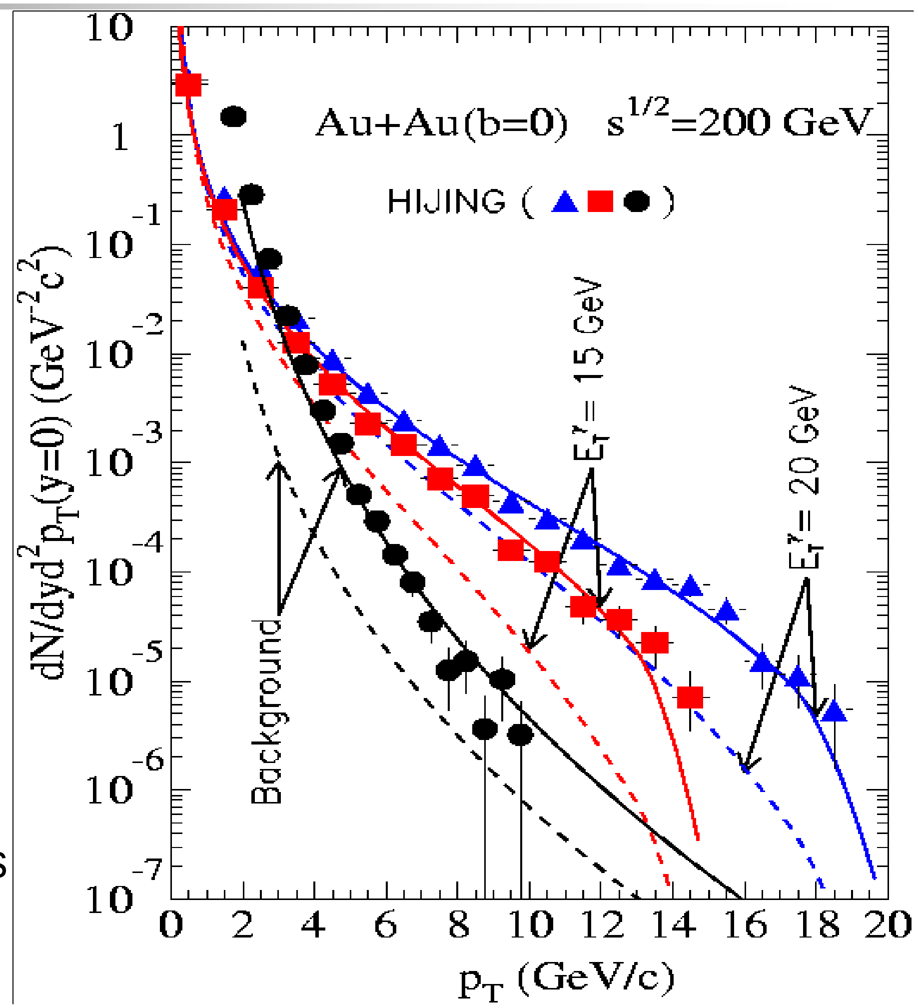
10^9 Central events



Precision Measurements
Tagged Jet quenching



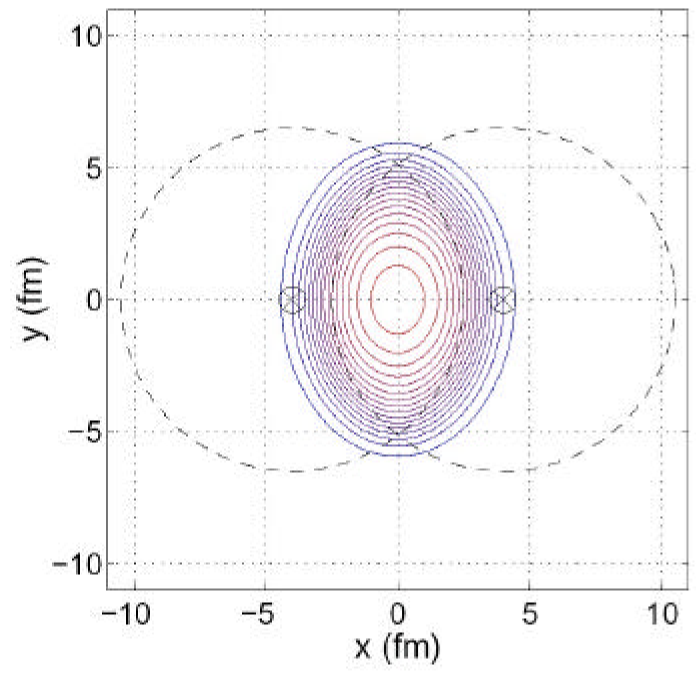
- Direct γ-tagged events: $\boldsymbol{E_g \sim E_{jet}}$
- Compare AA to pp
- Need to measure p_T spectrum of particles opposite high E_T g
  - g or p^0 ?
- Need to do this vs
  - Species/Energy to find energy loss
    - How big?
    - Proportional to mean free path?
    - Gluon/quark difference
  - P_T
  - Reaction Plane



➔ *Large back to back coverage*
- *EMCAL and tracking*
- *high pt pid would be good*

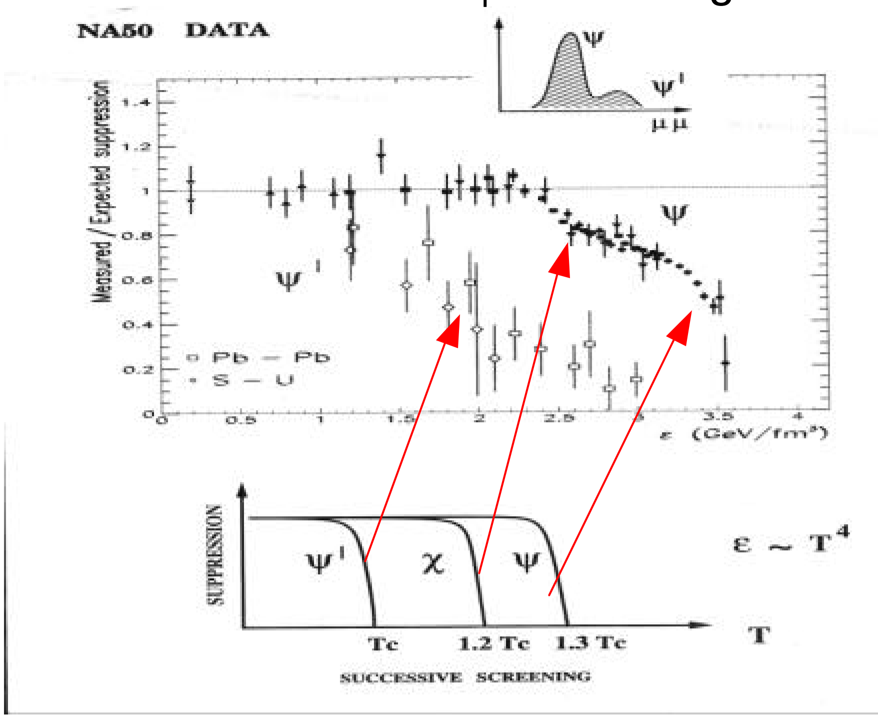
Tomography? (penetrating probes)

- Do as a function of "position"
  - Mass shift
  - Jet energy loss
  - Other?
- Requires
  - *Very High statistics*
    - *E.g. 10 bin in pt, 5 bins in y,5 bins in centrality, 8 bins in reaction plane*
    - *400 points per centrality; 2000 points*
  - *Good geometry measurements*
    - *Reaction plane/centrality – event by event*
  - Ability to invert data



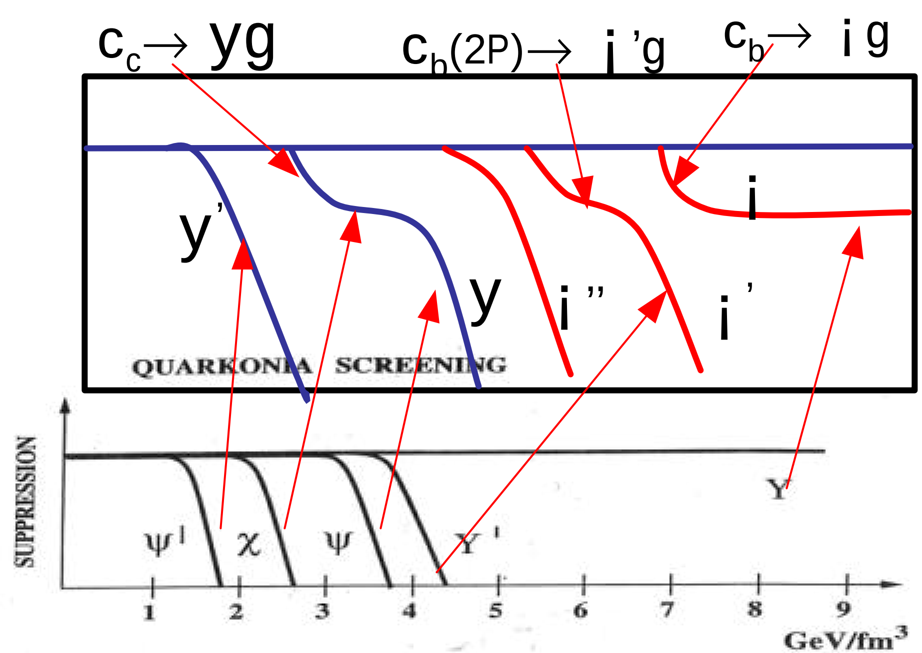
Onium Suppression

- SPS : Au-Au – 0.2-3.5 GeV/fm^3
  - Statistics on ψ’ was marginal !!



- RHIC – add ¡ to mix
- Rates (no suppression)
  - J/ψ Au-Au 0.4 x 10^6/yr
  - ϒ+ϒ’+ϒ’’ 1000 events 30 weeks

- RHIC (for a robust result)
  - Onium system as thermometer
    - p_T Dependence
    - $x_{1,2,F}$ Dependence
    - Study vs system size and energy
  - *Need High Rate*
  - *Large acceptance*
  - *Also critical to measure open charm*

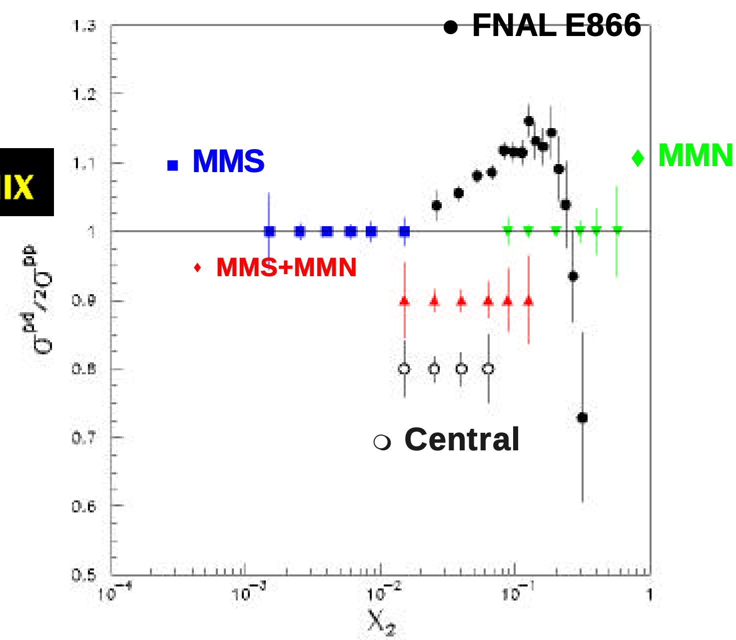


pA - a critical part of the RHIC program (2003-2005?)

- pA is critical for understanding AuAu collisions e.g. as a baseline for
  - onium suppression
  - Jet suppression
  - Just about any QGP signature you can think of
- pA is an important testing ground for QCD and is interesting in its own right for
  - Understanding parton distributions at low-x ~2x10^{-4}
    - E.g. gluon saturation
  - Understanding hard diffractive processes
    - E.g. parton structure of pomerons/mesons

- collider + large acceptance
  ➔ large kinematic reach

PHENIX



X_2 coverage via drell-yan in phenix
100x100 GeV^2 pAu

Improving the situation

- Measure associated jet to get x_1 , x_2 , Q^2
  - Very tough. Associated current jet is often at small angles and must me disentangled from the fragmentation jet which heads down the beampipe.
- *Improve muon acceptance with a very forward detector located in the tunnel.* $x_2 \sim 10^{-4}$ *for* $h > 1^{\circ}$
- *Large acceptance photon detector in the forward region*
- *Forward tagging via roman pots*
- *Tagging of nuclear fragments get a handle on* $N_{collisions}$

Physics with Polarized Protons at RHIC I(+)

Gluon Polarization: ΔG	$\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
$p^0, h^{+,-}$ Production $A_{LL}(gg, gq \to p^0, h^{+,-} + X)$ Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$ Direct Photon $A_{LL}(gq \to g + X)$ Jet Photon $A_{LL}(gq \to g + Jet + X)$ **PHENIX** **STAR**	W Production $A_L(u\bar{d} \to W^+ \to ln_l)$ **STAR +PHENIX**	Transversity h_1 : p^+, p^- Interference Fragmentation $A_T\left(p_\perp p \to (p^+, p^-) + X\right)$ Drell Yan $A_{TT}\left(p^\uparrow p^\downarrow \to (l^+, l^-) + X\right)$ **STAR +PHENIX+PHOBOS** Single Pion Asymmetries : $A_N(pp^\uparrow \to p + X)$ **STAR, BRAHMS**

Several rare event channels (which cannot be pre-scaled) must be taken in parallel!

Example, PHENIX level 1 rates at 500 GeV (from PISA):

W-trigger	11kHz
heavy flavor	4kHz
Transversity	6kHz
Other Channels	1kHz

==> twice available bandwidth! (12kHz)

$$R_{raw} = s \cdot L = 60\text{mb} \cdot 2 \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1} = 12\,\text{MHz}$$

Trigger and DAQ require upgrade

Some Suggestions for Spin Physics at RHIC II

Gluon Polarization : ΔG	$\frac{\Delta s}{s}, \frac{\Delta \bar{s}}{\bar{s}}$	Transverse Spin
Heavy Flavor with c,b-tagging Jet capability in PHENIX	W Production $A_L(sg \to cW \to l_1 l_2 + X)$	Use direct photon production for transversity measurements : p^+, p^- Interference Fragmentation $A_T\left(p_\perp p \to g + (p^+, p^-) + X\right)$ Collins Effect around jet axis $A_T\left(p_\perp p \to g + p^{+,-} + X\right)$ Drell Yan $A_{TT}\left(p^\uparrow p^\downarrow \to (l^+, l^-) + X\right)$ at high luminosities

- High luminosities from RHIC+ related DAQ and trigger upgrades
- Silicon vertex detectors
- Inner tracking with large geometric acceptance for PHENIX
- All upgrades should be compatible with the rate and data volume needs in pp!

Detector upgrades (Money is no object!)

- Tracking
  - Good momentum resolution - low mass states/high mass states
  - Perhaps very low pt
  - Large back to back coverage EMCAL and tracking
  - Jet coverage for pp – to measure x_1, x_2, Q^2
  - High rate capacity
  - Tag of detached vertex Dalitz rejection
- PID
  - high Pt hadrons
  - Leptons (mu/e,dalitz)
- Good geometry measurements
- pA stuff
  - forward muon detector located in the tunnel; $x_2 \sim 10^{-4}$ for $q > 1^{\circ}$
  - Large acceptance photon detector in the forward region
  - Forward tagging via roman pots
  - Tagging of nuclear fragments get a handle on Ncollisions
- DAQ
  - High Rate
  - High BW to "tape" (balance between acceptance and event count)
  - Good Level 1,2,3 triggering capability – at level 3 – sophisticated cuts

What about luminosity?

- You do need high luminosity for AA
  - Probes !
    - J/ψ family, ¡ family, jets (u,d,c,b,gluon), jet+ g Of these ¡, and high p_T jet+g (E_T > 15 GeV) are the lowest cross sections
      - jet+g(E_T > 15 GeV): ds/dy/dp_T(y=0) = 5x10^{-4} mb/GeV
      - ¡ : (ds/dy)BR =8.6x10^{-5} mb
        - Look at rates for this
      - Study processes ~ 10^{-4} mb ~ 1000 events in 30 weeks
  - Detector capabilities
    - Large acceptance
    - High rate (triggering+daq band width)

How much? x40

- Require ~5000 U events (5 bins of centrality ~ 3% measurement – more if in p_T bins)
  - 150 weeks at blue book, 40 weeks at 4xbluebook
  - Too much if we want to do various species/energies in a reasonable amount of time
  - 4 weeks at 40x Bluebook – acceptable.
- For pA and pp, high luminosity is also required for
  - DY – 35 weeks for 1000 events at bluebook, M~5GeV
    - ~1 week/1000 events at 40x bluebook
  - W boson
    - I note that the spin folks also should get an energy upgrade to 650 since the W cross section is rapidly rising in this region

Detector requirements - Tracking

- *Good momentum resolution*; if Dp/p=a+b*p
  - low mass states – measure well the width
    - Dm_f ~ 2MeV – Want the constant term a~ 0.2%
      - Bend angle measured early before too much material
  - high mass states – separate U(9460) U' (10023) U"(10355)
    - 100-200 MeV at high mass b~ 0.2%
      - Need 100 mm resolution and good vertex position with 1T field, or high field
- very low pt ~ 50 MeV
  - Low Magnetic field – no material
      - Bend angle measured early before too much material
- Large back to back coverage EMCAL and tracking
  - *2p Coverage*
- Jet coverage for pp – to measure x1,x2,qsq
  - *2p Coverage*
- *High rate capacity*
  - High Level 0 Rate – at RHIC II Luminosity (40xdesign)
    - In AuAu – 60KHz Min bias, SiSi is 50x that
    - In pp – rate is ~240MHz (4x10^{33} 500 GeV-20x design)

PID

- Leptons (m/e,dalitz)
  - Leptons are our penetrating probes and critical for understanding RHIC physics
    - e/p below level of electron background
      - 10^{-3} without dalitz rejection
      - 10^{-4} with dalitz rejection
- high Pt hadrons
  - To resolve the proton/kaon/pion puzzle
    - P/K/**p** to 3-4 GeV (**p**/p Cross over is ~ 2 GeV)
    - Smaller coverage OK
  - K^- ($\bar{u}s$) can be used as a gluon tag
    - PID to as high as possible to look at gluon energy loss
    - Large coverage (low rate)

Special capabilities

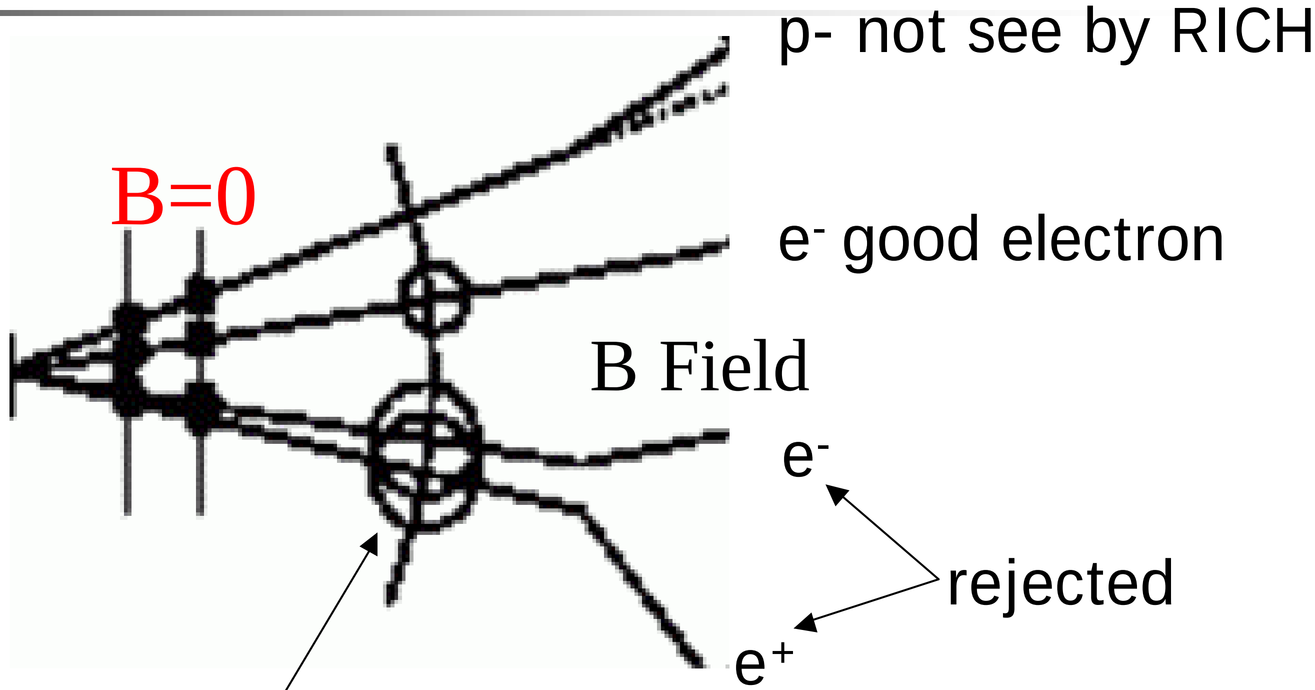
- Vertex Tracking
  - Identification of Charm, Bottom
  - ct(charm) ~ 125-300 mm, ct(bottom) ~ 500 mm
    - *Identify vertex to ~ 50 mm*
  - Trigger
    - On moderate pt lepton – probably limits one to high pt D/B mesons
      - Rate of moderate pt leptons?
    - On detached vertex? (Level 3) – you get most of them

- Special forward detectors for pA (eA later?)
  - *Tagging of nuclear fragments get a handle on Ncollisions*
    - *Necessary for pA studies for AA*
  - forward muon detector located in the tunnel; x_2~10^{-4} for q>1°
  - Large acceptance photon detector in the forward region
  - Forward tagging via roman pots

A schematic of dalitz rejection

- Reject ~90% of dalitz

  ➔Reduce combinatoric background by factor of 100
- Problem- real electron pairs from charm



- Features
  - Field free region
  - Inner tracker
  - Hadron blind Ring Imaging Cerekov's (RICH)- sees only electrons
- Dalitz suppression
  - Dalitz Pairs have small opening angle since field free region near vertex
  - Close rings in RICH

Rate- the DAQ (a major issue)

- High Level 0 Rate – at RHIC II Luminosity (40xdesign)
  - In AuAu – 60KHz Min bias, SiSi is 50x that
  - In pp – rate is ~240MHz ($4x10^{33}$ 500 GeV-20x design)
  - (archeology – PHENIX CDR –11KHz AA, 150Hz to tape!)
- High BW to "tape" (balance between acceptance and event count)
  - TPC like detectors have a huge data volume
  - We are increasing the luminosity by 40
- Presumably our DAQ becomes faster
  - Can RCF handle say 1GB/sec? (10M s/yr~10 petabyes/yr)
- Good Level 1,2,3 triggering capability – at level 3 – sophisticated cuts
  - Some triggers "easy" (e.g. high pt)
  - Many involve sophisticated event topologies
    - Detached Vertex
    - Events with electrons AFTER Dalitz rejection
    - Require On-line reconstruction at high speed
  - If we are after 20 different topologies
    + min bias each topology only gets ~3% of the BW!
- Are we bold enough to write ONLY DST's?

Star has a beautiful online event reconstruction- but slow
PHENIX has Level 2 trigger at "full" speed, but crude
These need to come together

A bit of common sense

- Redundant results are important
  - The fact that there are 2 or more detectors measuring similar things is a *strong feature* of the program, not a problem
- Keep pA and eA in mind as we upgrade

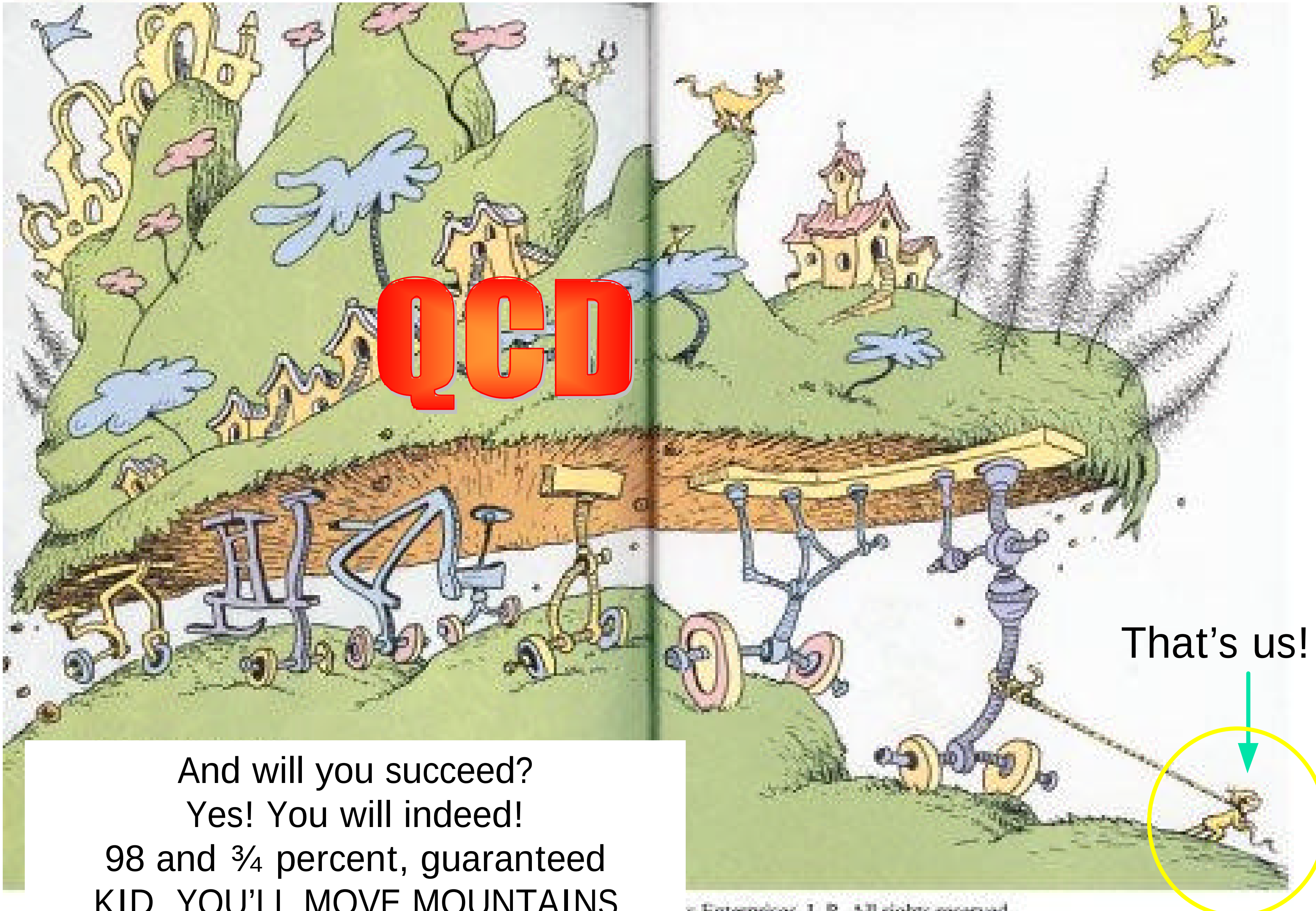
Priorities (my list)

- Running Time! (Make sure we get this)
- Major Detector Upgrades (R and D + request the funding)
  - Dalitz rejection
  - High pt+PID
  - Charm (Good vertex detection)
  - Extend di-electron capabilities to other detectors for redundancy
  - Extend Jet detection capabilities to other detectors- pp
- For pA
  - Forward detectors
- Major Luminosity upgrade (x10 electron cooling)
  - For Onium states, χ-jet , DY, W/Z .....
  - May entail major upgrades to detectors
    - large acceptance (2p)
    - high rate (DAQ+triggers)

A summary : Philosophy

- RHIC provides us with a powerful QCD laboratory
  - AA, pA (dA), pp, eA
- Theory + Experiment = Understanding
  - ***Theoretical Calculations*** in regions probed by ***experiment***
  - ***Experiments*** in regions calculable by ***theory***
- New era of Precision
  - Precision ***Calculations***
  - Precision ***Measurements*** (this workshop)
    - Precision Detectors
    - High Luminosity

➔Demands on Machine and detector



And will you succeed?
Yes! You will indeed!
98 and ¾ percent, guaranteed
KID, YOU'LL MOVE MOUNTAINS